Post-Linac Collimation Systems for the European XFEL and for the FLASH Facilities

Vladimir Balandin
DESY

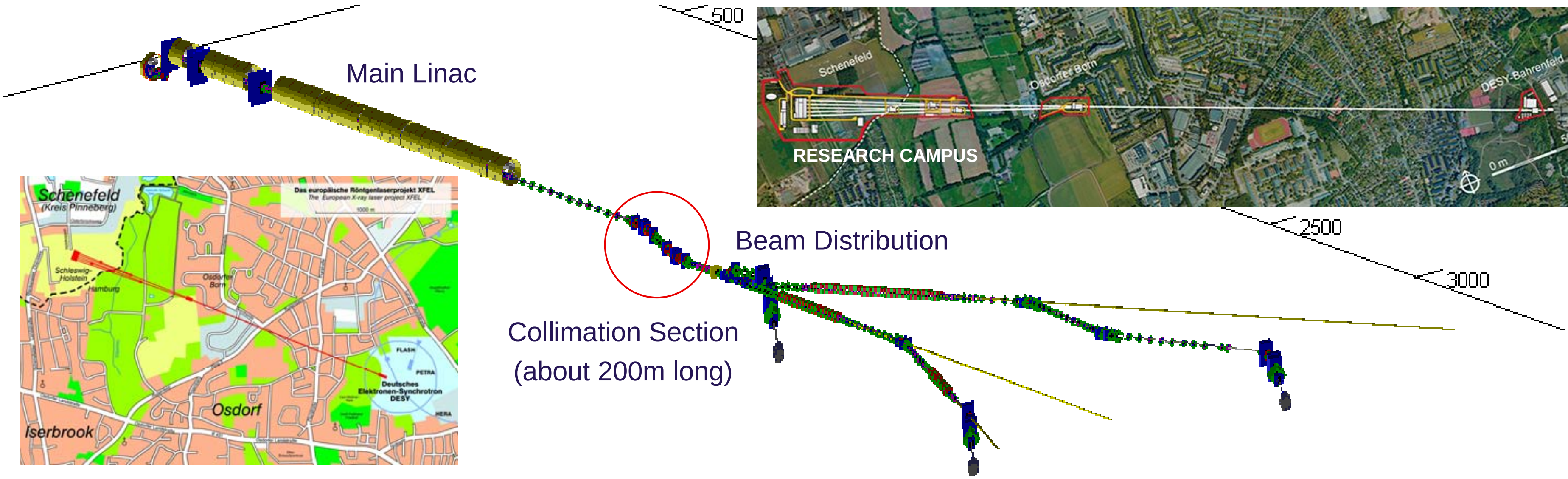
Importance of Collimation

- In first place, during routine operations, electron beam collimation is necessary in order to remove off-momentum and large amplitude halo particles, which could be lost inside undulator segments and become the source of radiation-induced demagnetization of undulator permanent magnets.

- The collimation system also must protect undulator segments and other downstream equipment against miss-steered and off-energy beams in the case of machine failure without being destroyed in the process.

- Post-linac collimation system is in operation at FLASH and LCLS facilities and will be used at the European XFEL facility (some possibilities for removing of parasitic particles are also foreseen at SCSS).

Collimation System for the European XFEL



Specific for the European XFEL:

From the beam dynamics point of view, the collimation section, as a part of the beam transport line from linac to undulator, should be able to accept bunches with different energies (up to ±1.5% from nominal energy) and transport them without any noticeable deterioration of beam parameters, i.e. it must be sufficiently achromatic and sufficiently isochronous.

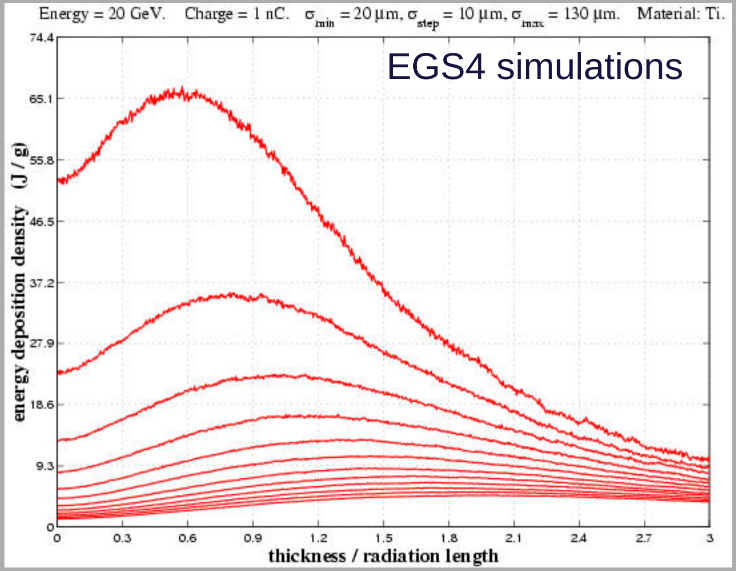
This will allow to fine-tune the FEL wavelength by changing the electron beam energy without adjusting magnet strengths and, even more, will allow to scan the FEL wavelength within a bunch train by appropriate programming of the low level RF system.

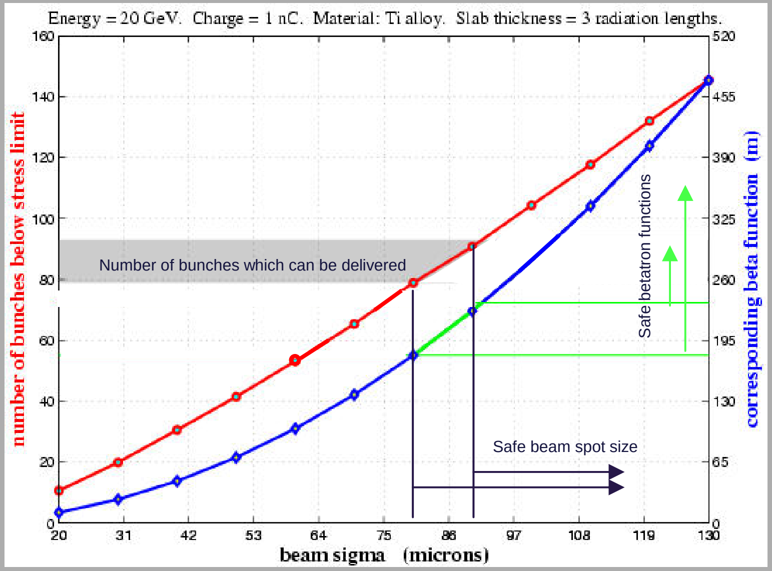
- V.Balandin, R.Brinkmann, W.Decking, N.Golubeva, "Optics Solution for the XFEL Post-Linac Collimation Section", TESLA-FEL 2007-05
- V.Balandin, R.Brinkmann, W.Decking, N.Golubeva, "Post-Linac Collimation System for the European XFEL", Proceedings of PAC09, Vancouver, BC, Canada

Collimator Material

Emergency Scenario:

Detect a failure and switch the beam production off as quickly as possible

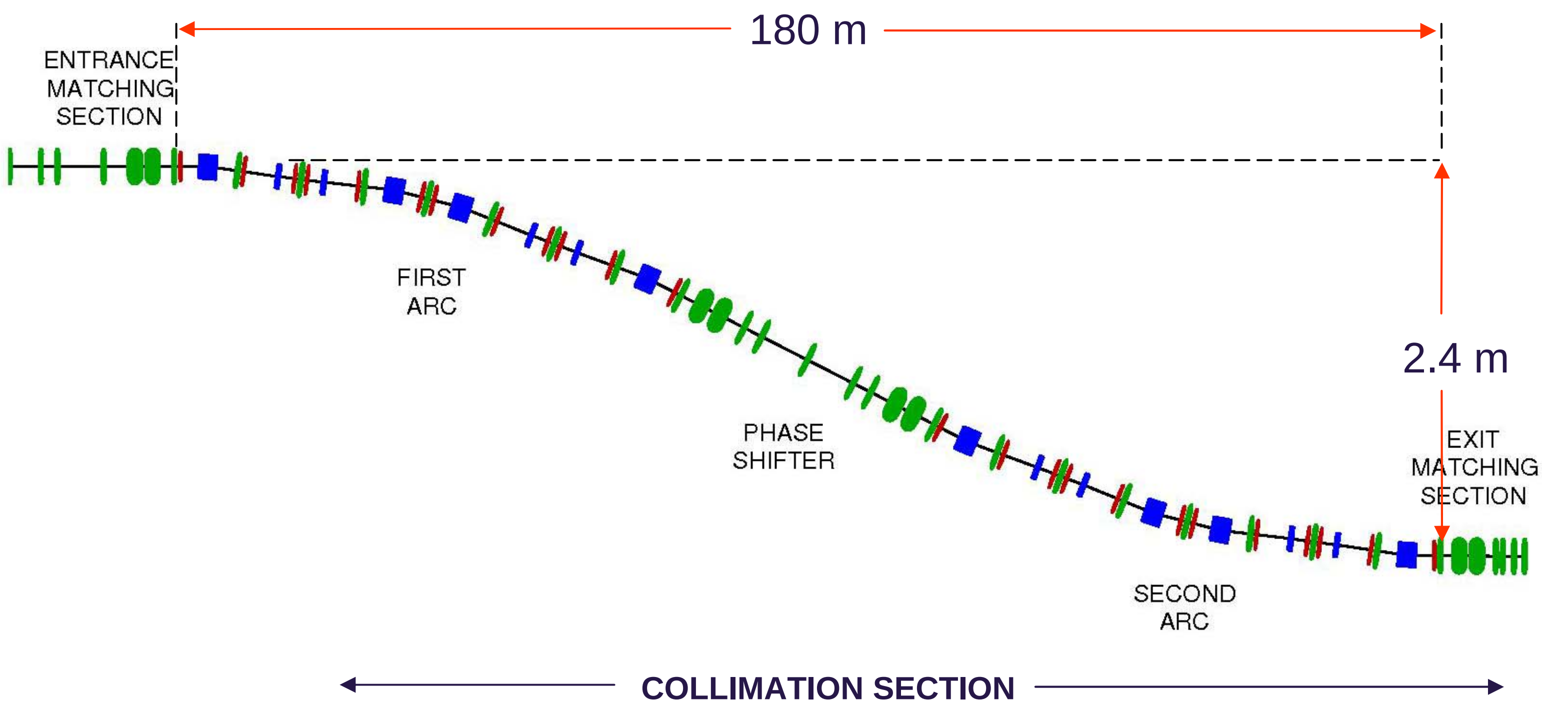




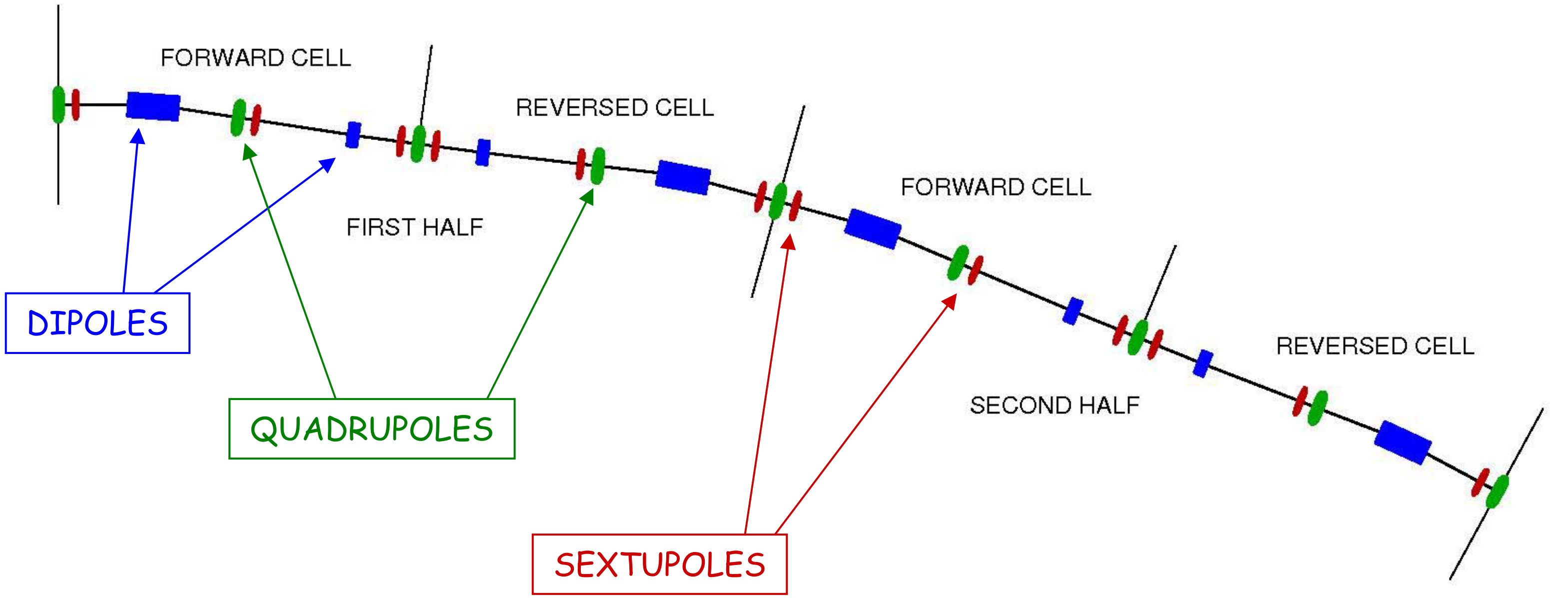
Candidate for Collimator Material: Titanium Alloy

Stress analysis shows that to withstand a direct impact of such number of bunches (~100) which can be delivered to collimator location until failure will be detected and the beam production will be switched off, the beam spot size should be not smaller than 80-90 microns (energy: 20GeV, normalized emittance: 1.4 mm·mrad, bunch charge: 1 nC, bunch spacing: 200 ns).

Layout and Functionality



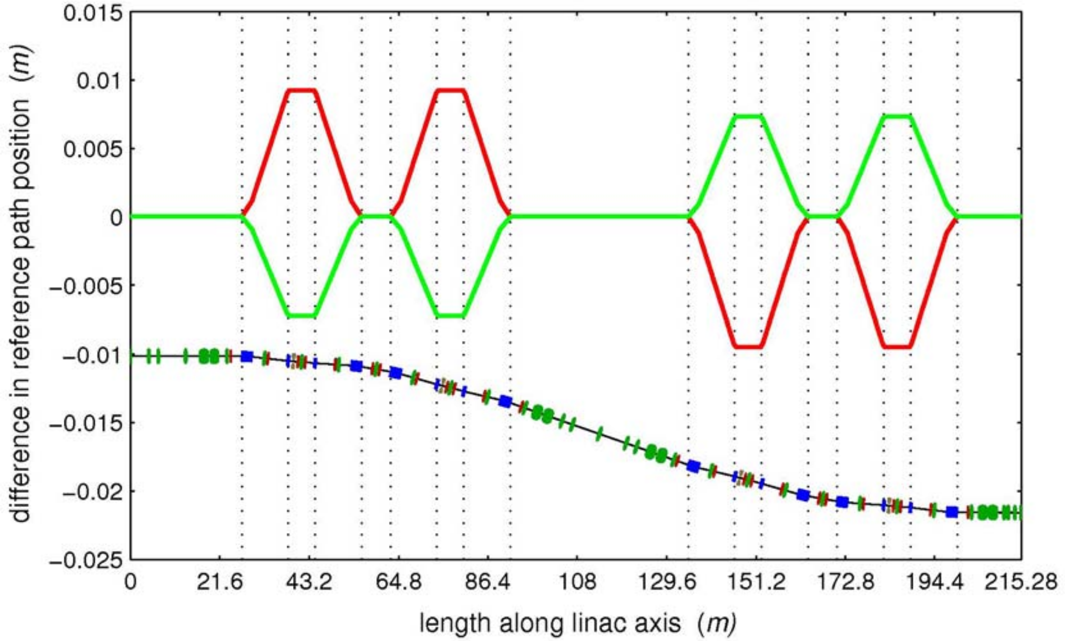
Layout and Functionality



Each arc consists of four 90⌖ cells, constitutes a second-order achromat, and its R56 can be adjusted by system realignment in such a way that R56 of the total collimation section can be varied within ⌖1 mm limits (the baseline design is the beam line with R56 = 0).

- V.Balandin, R.Brinkmann, W.Decking, N.Golubeva, “Two cell repetitive achromats and four cell achromats based on mirror symmetry”, Proceeding of IPAC10, Kyoto, Japan
- V.Balandin, R.Brinkmann, W.Decking, N.Golubeva, “Apochromatic beam transport in drift-quadrupole systems”, Proceedings of IPAC10, Kyoto, Japan

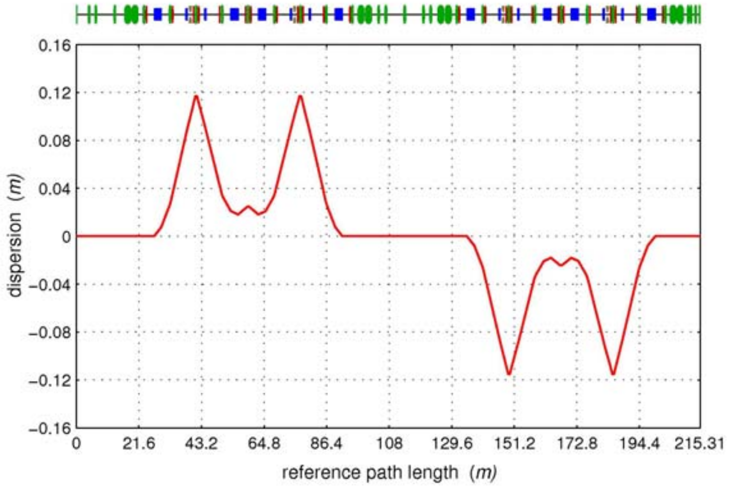
Passive Adjustment of Linear Isochronicity

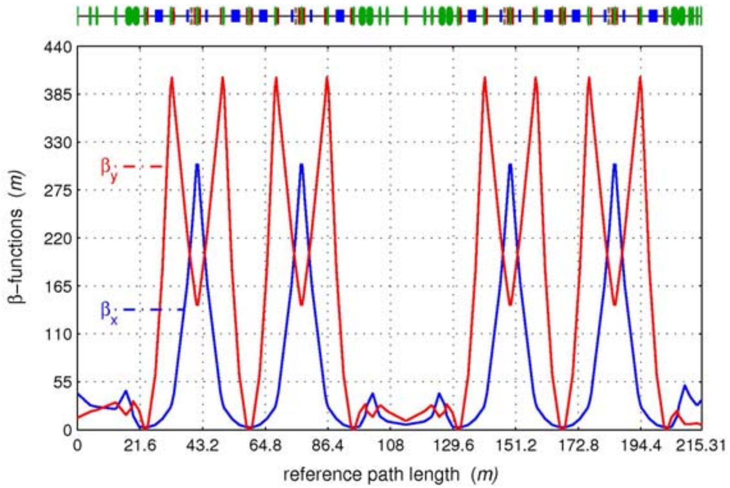


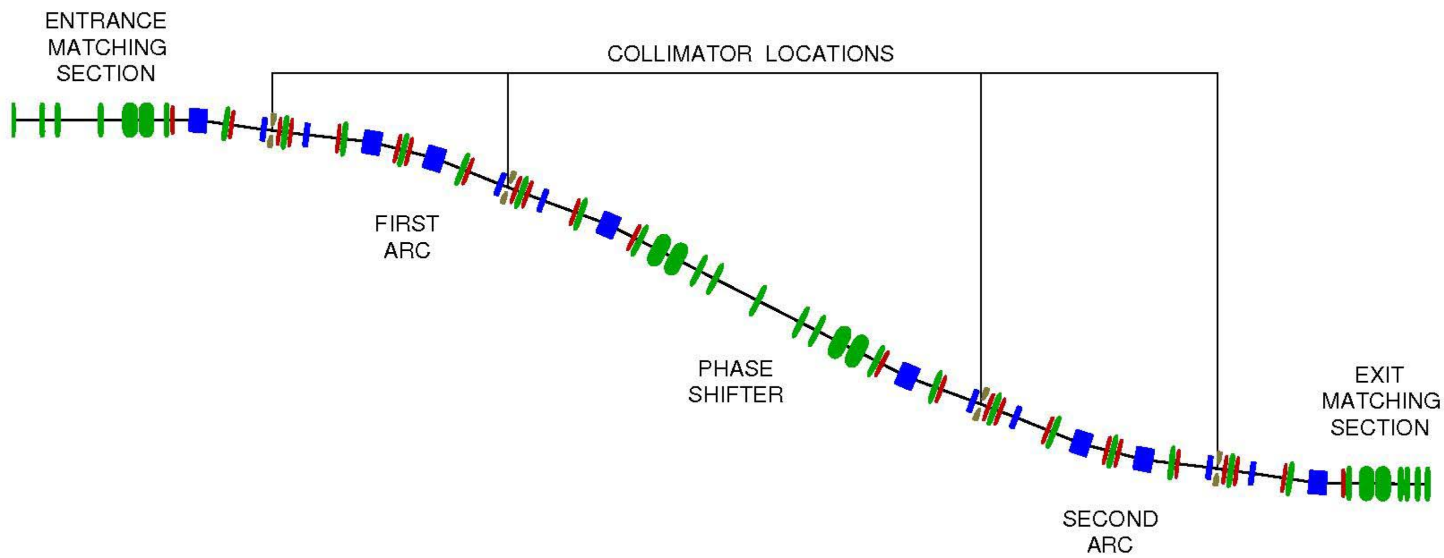
Changes in the vertical position of isochronous beam line with R56 = 0, which are required to bring linear momentum compaction of the collimation section to R56 = -1 mm (red curve) and to R56 = +1 mm (green curve).

The space positions of the system end points, the straight sections and the arc centers are kept unchanged, as it can be seen in figure.

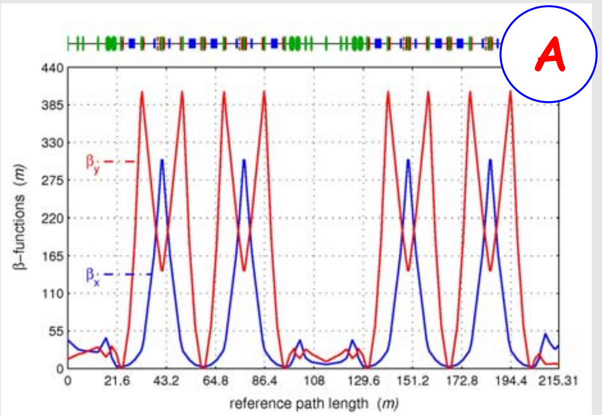
Linear Optics Functions and Collimator Locations

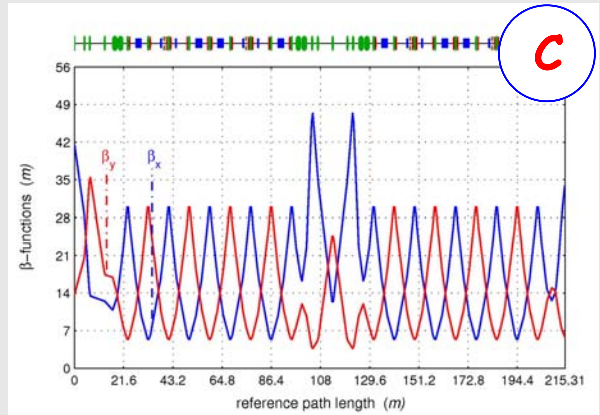


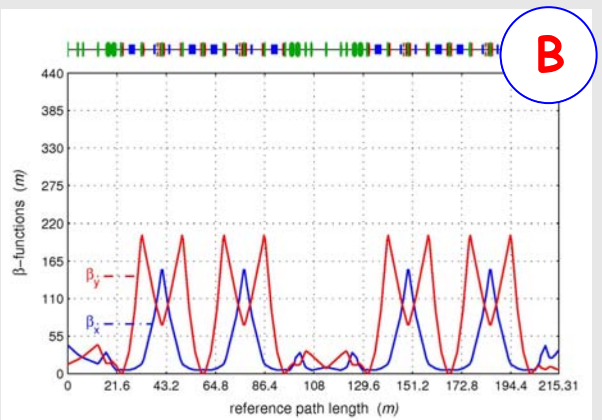


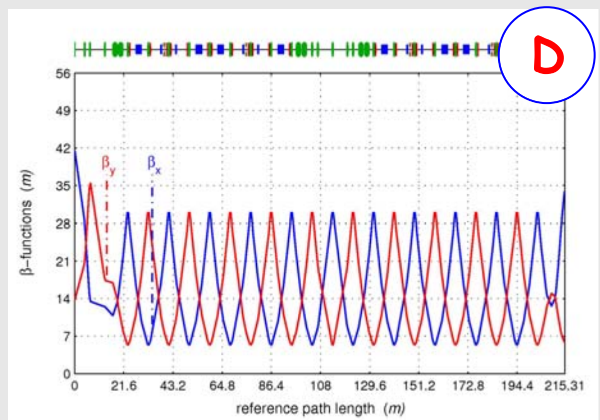


Optics Flexibility







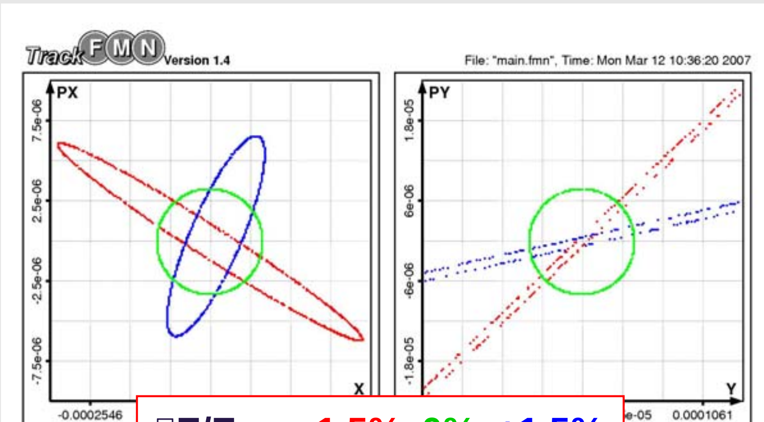


Without touching arc magnets and by tuning only quadrupoles in the matching sections and phase shifter, the betatron functions could be varied (A, B,C). This tuning includes also the possibility of FODO-like transport through the whole collimation section (D). It could be useful feature for commissioning and measurements.

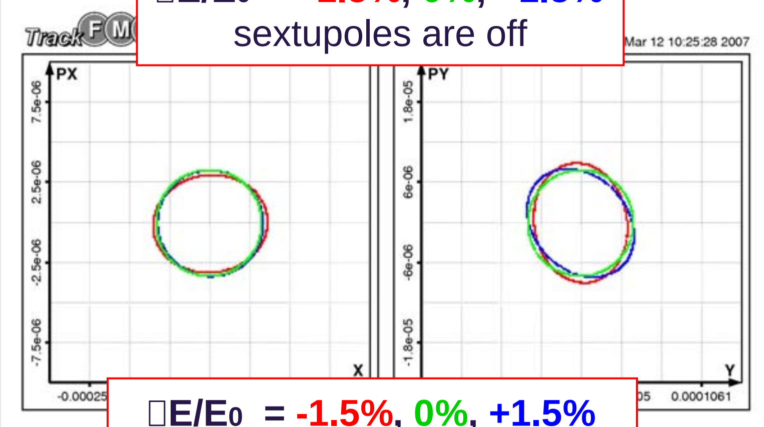
The possibility of betatron function tuning combined with exchangeable apertures of collimators will allow to regulate the transverse and energy collimation depths separately, despite that collimators are placed in the dispersive region of the beam line.

Beam Dynamics: Energy Offset and Nonlinearities

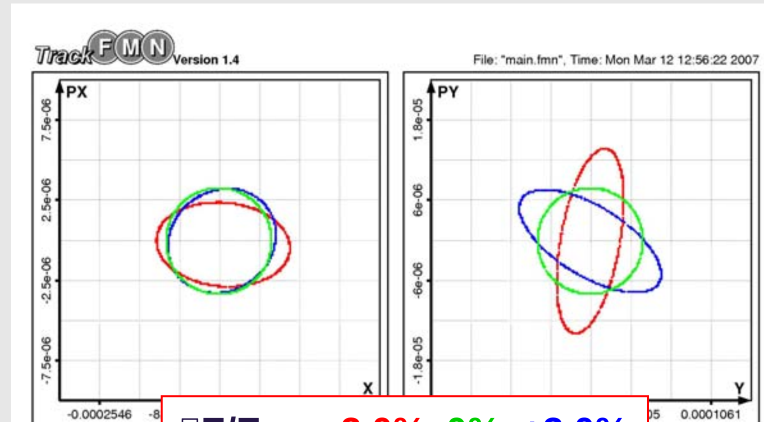
Beam transfer properties of the collimation section
(including matching sections and phase shifter).



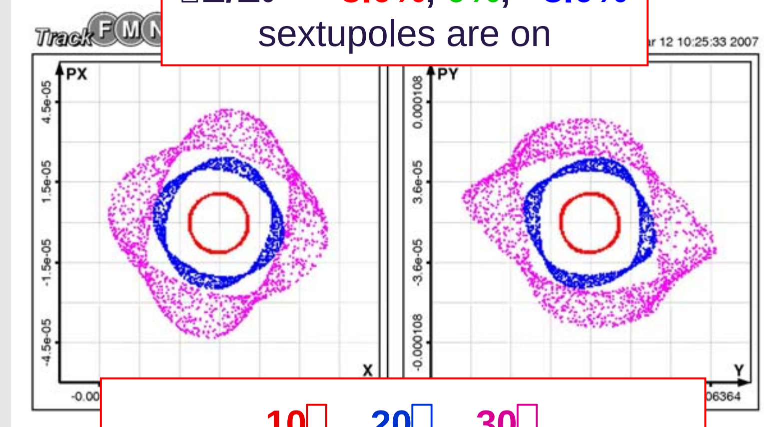
$\Delta E/E_0$ = -1.5%, 0%, +1.5%
sextupoles are off



$\Delta E/E_0$ = -1.5%, 0%, +1.5%
sextupoles are on

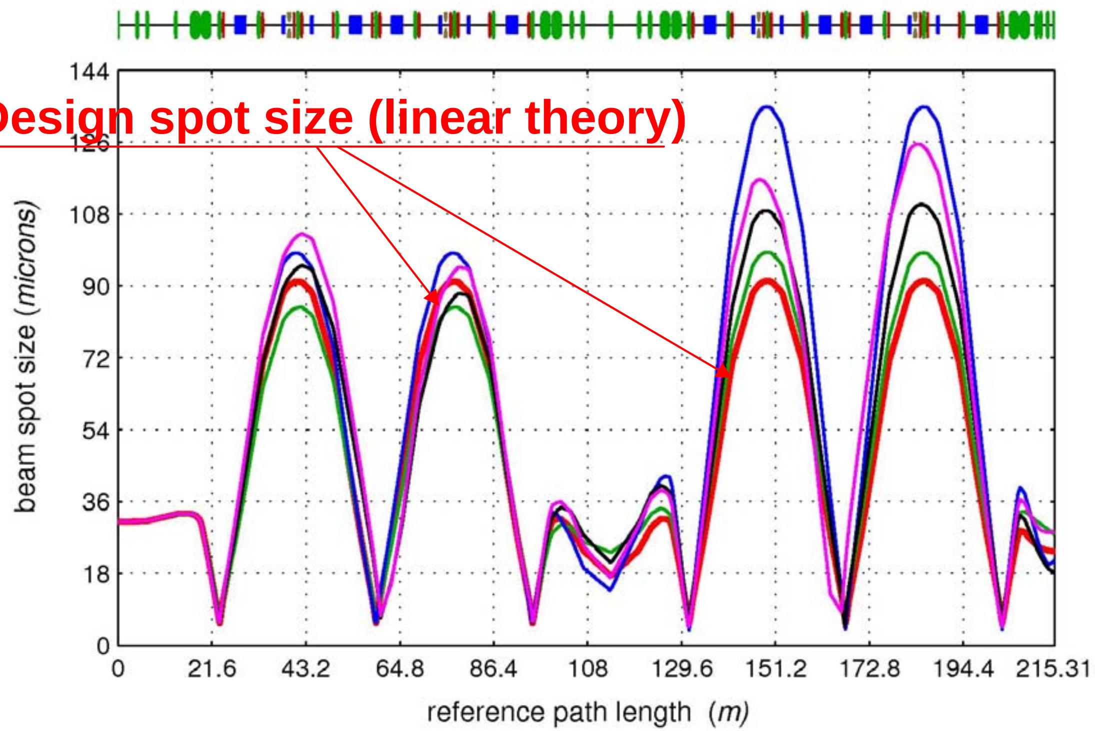


$\Delta E/E_0$ = -3.0%, 0%, +3.0%
sextupoles are on



10□ 20□ 30□
$\Delta E/E_0$ = 0%, sextupoles are on

Effect of Energy Offset and Nonlinearities on Evolution of Beam Spot Size Along Collimation Section



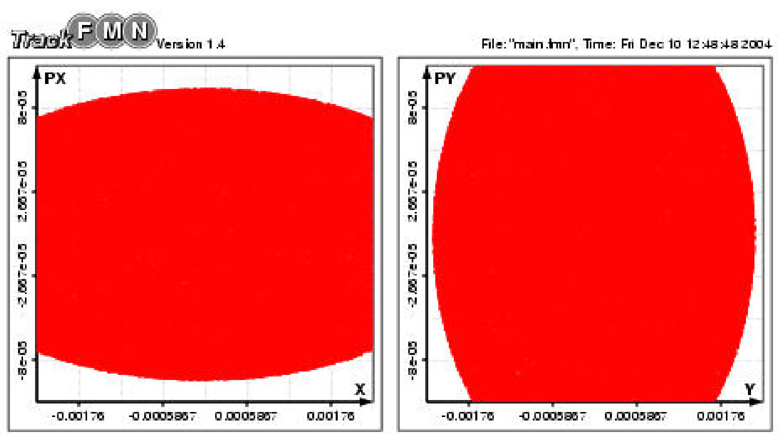
Beam spot size (rms) extracted from accurate tracking simulations:

Matched Gaussian beam at the entrance with energy offset -3% (blue), with energy offset +3% (green), with y-offset 40⇔ (black), with both energy offset -3% and y-offset 40⇔ (magenta). Beam energy 17.5 GeV, normalized emittance 1.4 mm▯mrad.

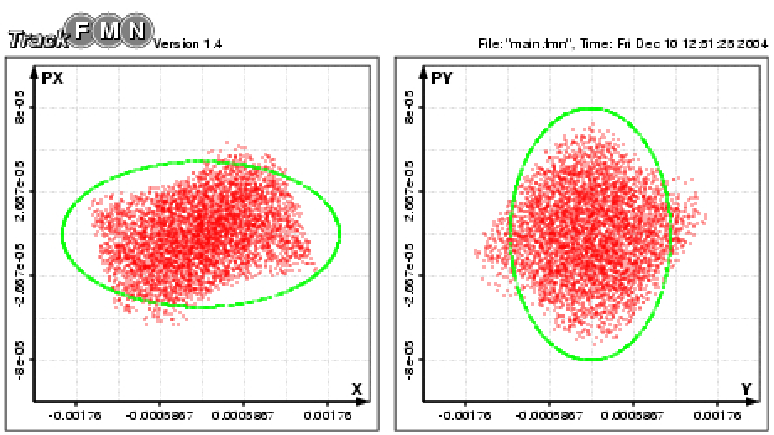
Estimate of Required Collimator Apertures

Calculation Algorithm:

1. Define the phase space volume which must contain all particles at the exit of the collimation section.
2. As initial distribution at the entrance of the collimation section take a monochromatic 4-dimensional distribution, which in the projection on the real space covers all vacuum chamber aperture.
3. By accurate numerical tracking and using black absorber model for the collimators find the maximal possible collimator radii, which guarantee that all particles which have passed the collimation section are inside the target ellipses.
4. Repeat calculations for the initial distributions with different energy deviations and plot results as a function of the energy deviation.

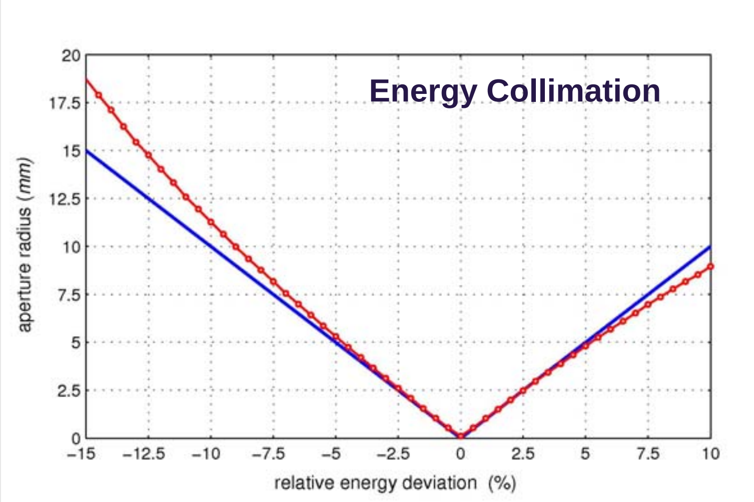


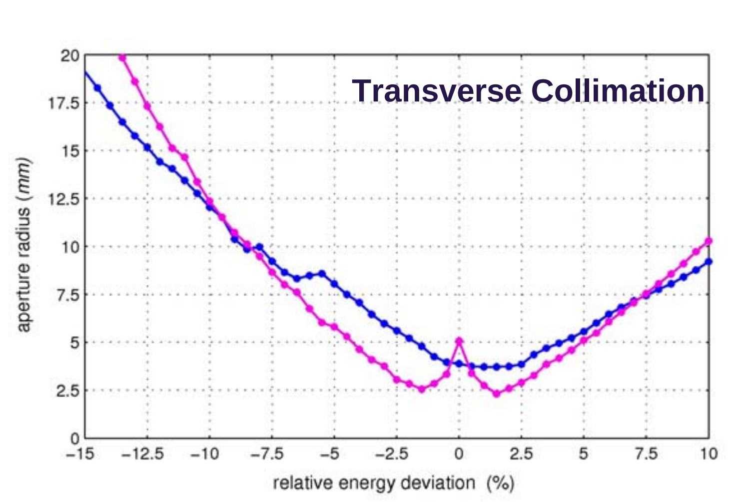
Initial distribution at the system entrance.
All particles have the same energy.



Non-collimated particles at the system exit. Some of them are outside of the target ellipses. So repeat calculations with smaller collimator radii.

Estimate of Required Collimator Apertures





Red curve:
Aperture radius required to block the corresponding off-energy fraction of incoming particles in the collimation section.

Blue curve:
Analytical estimate for this radius made using linear dispersion at the collimator location.

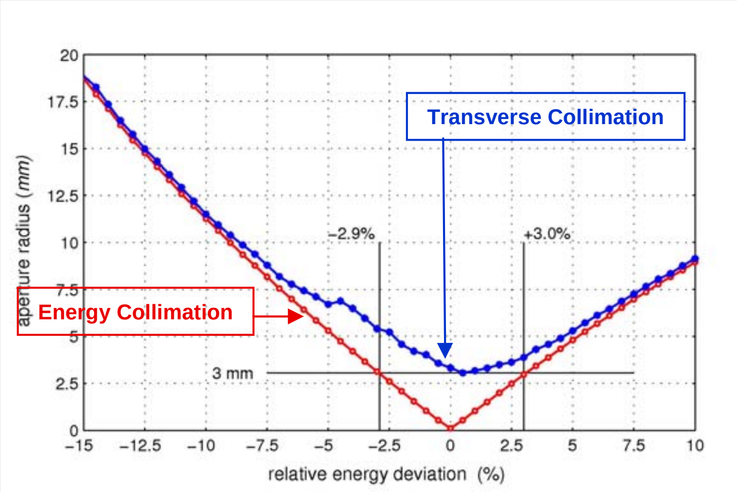
Optics A with sextupoles switched on.

Aperture radius required to protect the undulator vacuum chamber (radius = 4 mm) as a function of the energy deviation.

Optics A with sextupoles switched off (magenta curve) and on (blue curve).

Sextupole magnets in the collimator section not only improve beam dynamics, but also allow to use collimators with larger radii.

Estimate of Required Collimator Apertures

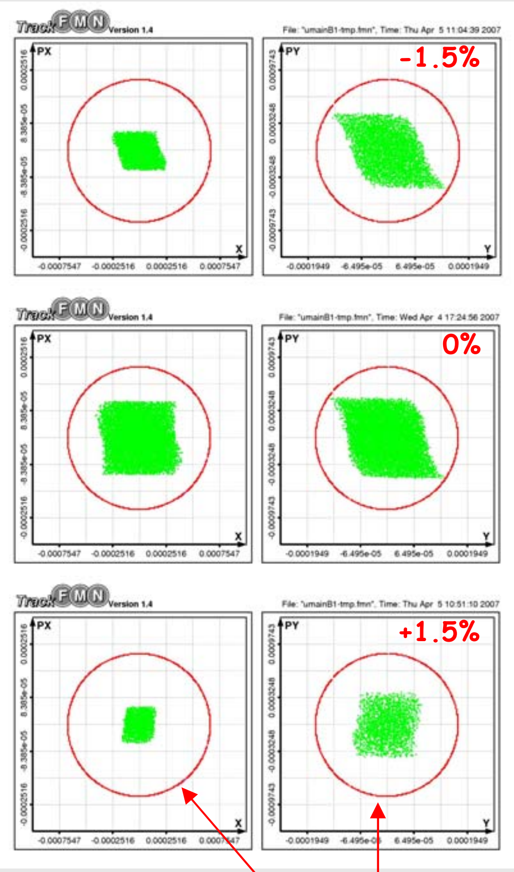


Blue curve:
Aperture radius (of all 4 collimators) required to protect the undulator vacuum chamber with 3mm radius (with safety factor, minimal aperture in undulator is 4 mm) as a function of the energy deviation.

Red curve:
Aperture radius required to block the corresponding off-energy fraction of incoming particles in the collimation section.

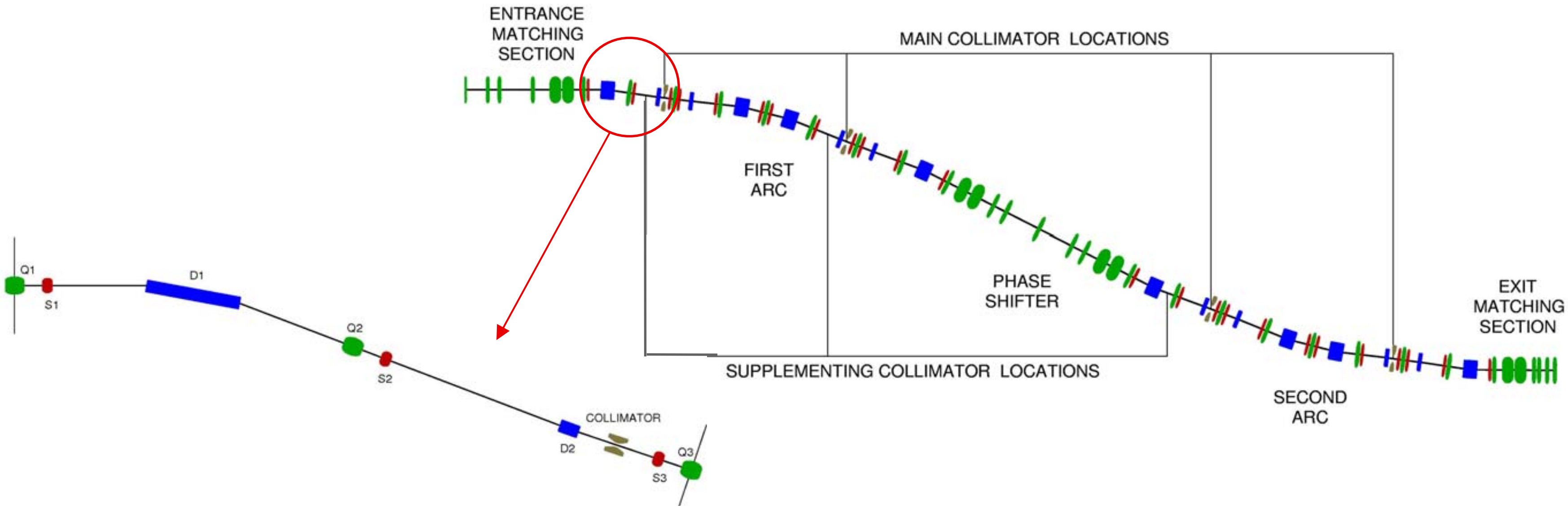
Optics A with sextupoles switched on.

Particles at system exit (green):
Beams with different energy offsets will be collimated differently.



TARGET ELLIPSES
(~60□ at 17.5 GeV, 1.4 mm mrad)

Collimators



Three types of collimators are foreseen:

- 4 main primary collimators with exchangeable apertures to intercept all primary particles which would otherwise appear outside of the downstream dynamic aperture.
- Supplementing primary collimators to help primary collimators to shade a beam pipe from uncontrolled beam losses (the example: 3 supplementing collimators with aperture radii 10 mm).
- Secondary collimators (absorbers) placed in the shadow of primary collimators to improve the cleaning efficiency at the exit and better localize losses inside the collimation section.

(The number and locations of supplementing primary and secondary collimators are not fixed yet.)

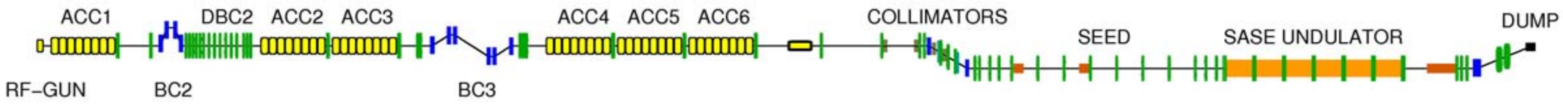
Free-electron laser FLASH - pilot facility for the European XFEL

- FLASH is a free-electron laser at DESY which was commissioned in 2004 and has been used for research with shortwave ultraviolet and soft X-ray radiation since 2005.

- The facility is about 260 metres long and generates soft X-ray radiation down to a wavelength of 4.45 nanometres (after a major upgrade during last winter).

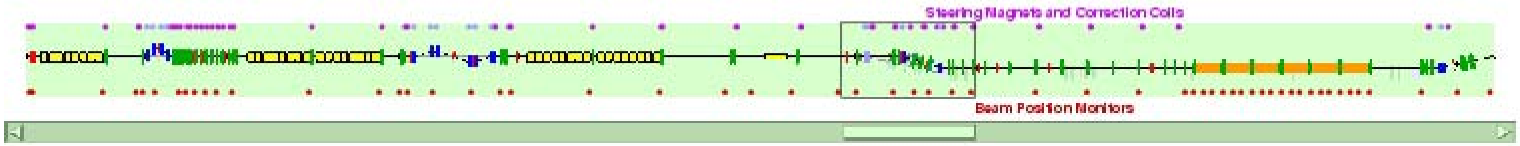
- Until 2009, FLASH was the only free-electron laser in the world to produce radiation in the soft X-ray region.

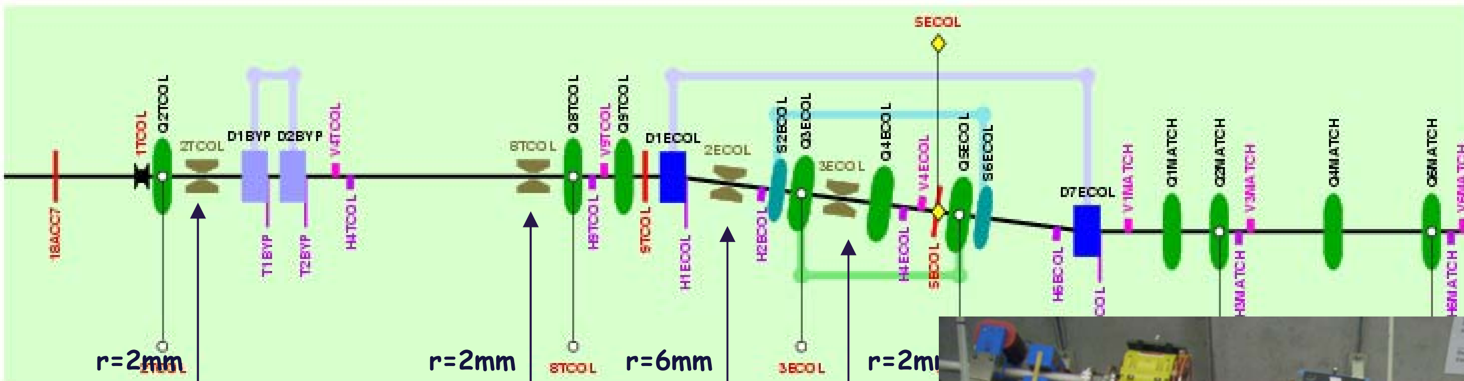
- FLASH is a small version of the European XFEL . The facilities differ mainly in the wavelengths of the generated light flashes.



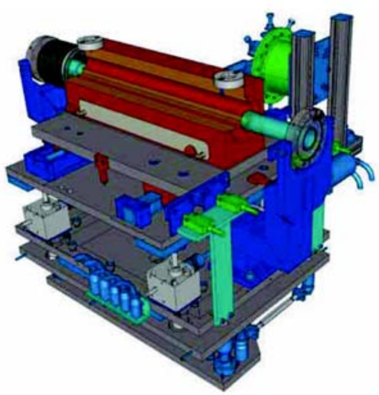
The 30 m long undulator consists of permanent NdFeB magnets with a fixed gap of 12 mm, a period length of 27.3 mm and peak magnetic field of 0.47 T.

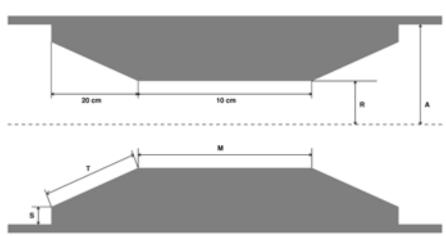
FLASH Collimator Section





Four collimators (copper)

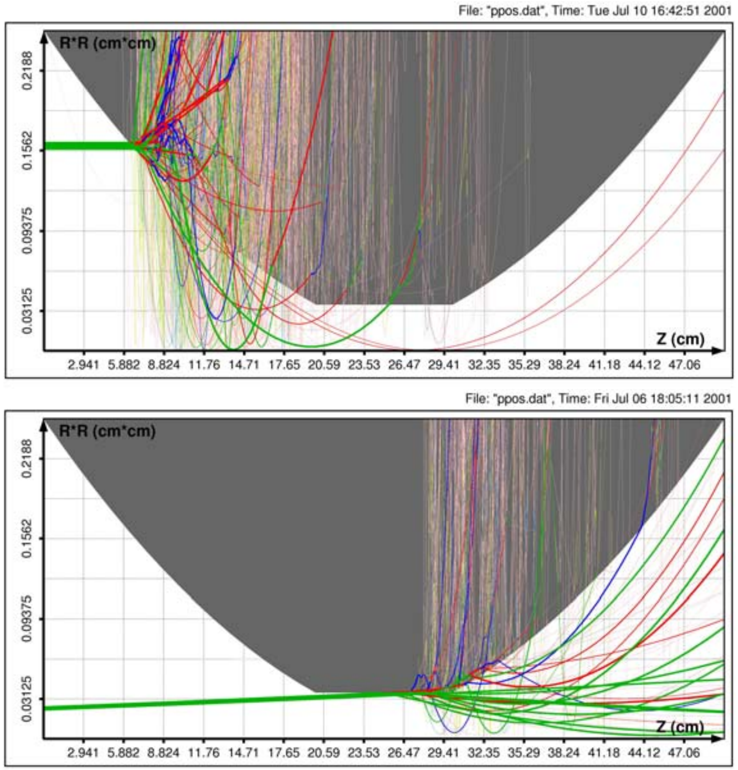




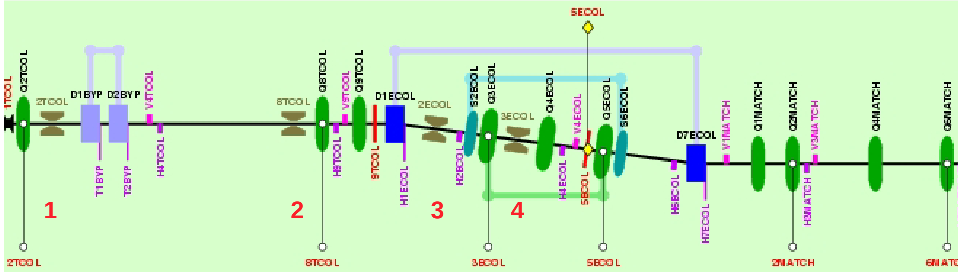
🕓 V.Balandin, K.Flottmann, N.Golubeva, M.Korfer "Studies of the Collimator System for the TTF Phase 2", TESLA 2003-17

Study of the FLASH Collimator Section

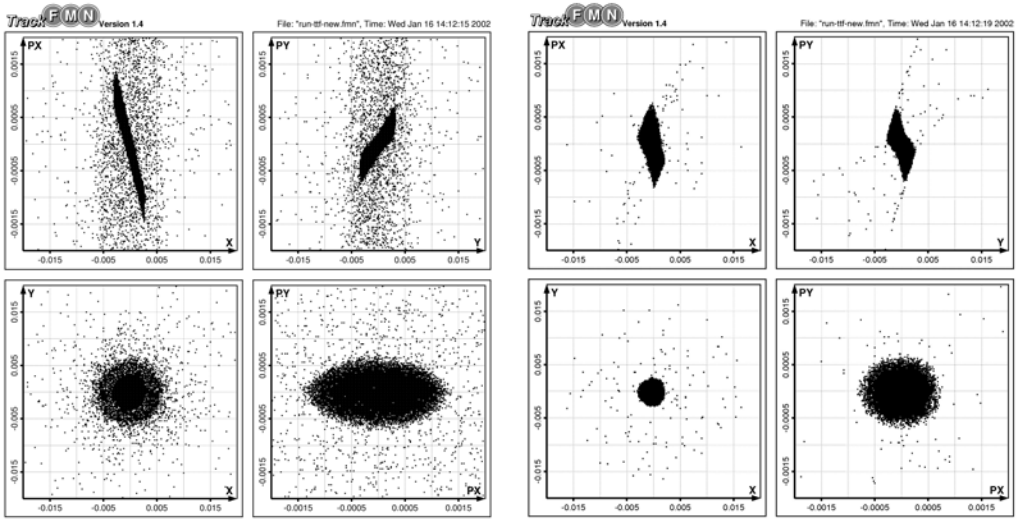
Example of the study of the FLASH collimation system:



Scattering, production of secondary particles, and development of the electromagnetic shower in the collimator made from copper. EGS4 simulations (green, blue and red trajectories correspond to electrons, positrons and photons).

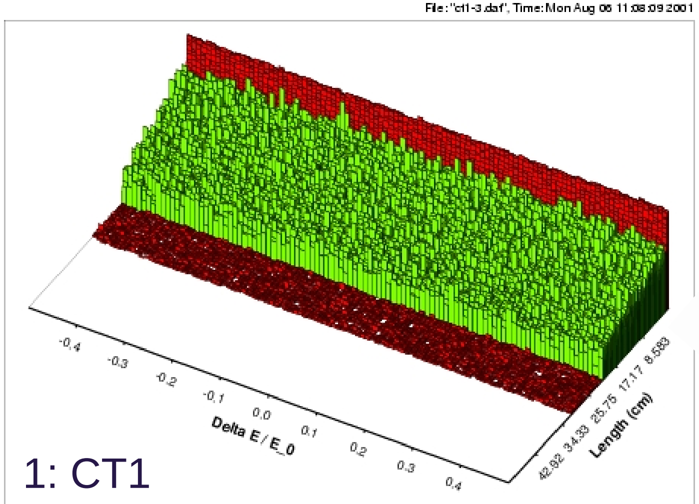


Tracking with Gaussian halo model (sigma halo = 25 beam sigma): very few particles are able to reach the undulator entrance

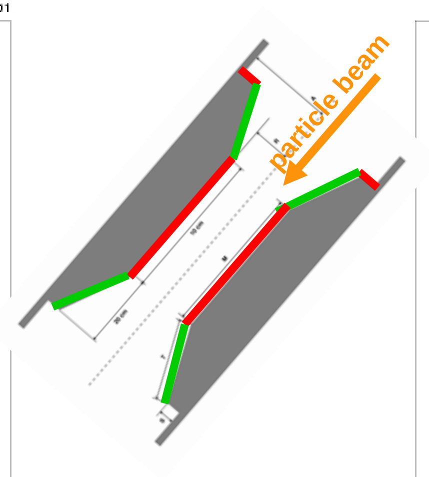


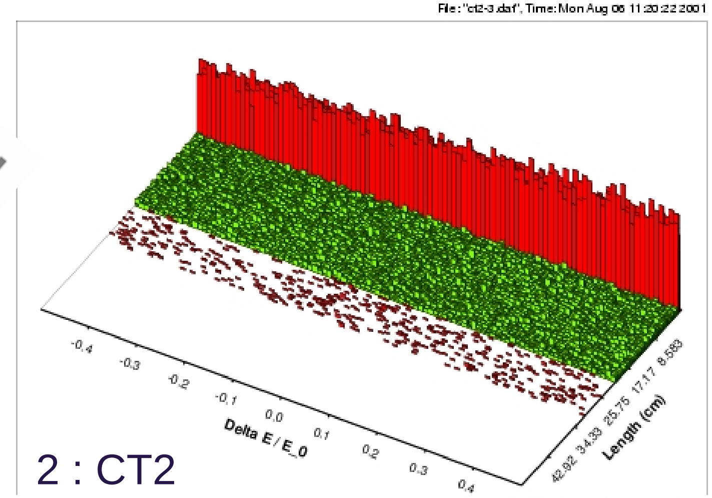
Phase space portraits of primary and secondary particles at the exit of the second collimator and at the exit of the fourth collimator.

Study of the FLASH Collimator Section



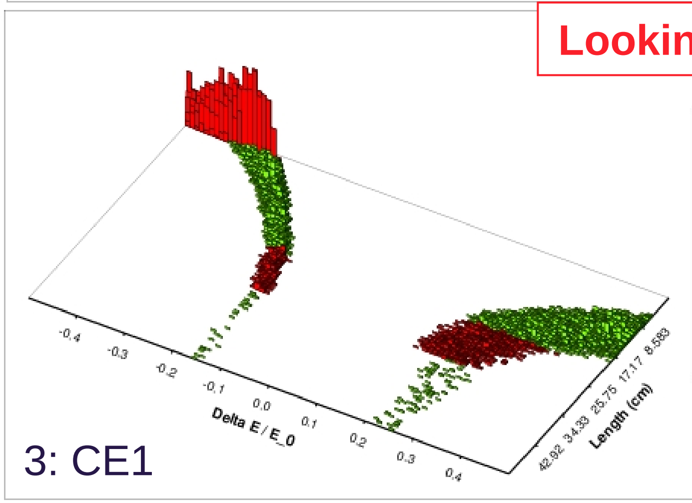
1: CT1



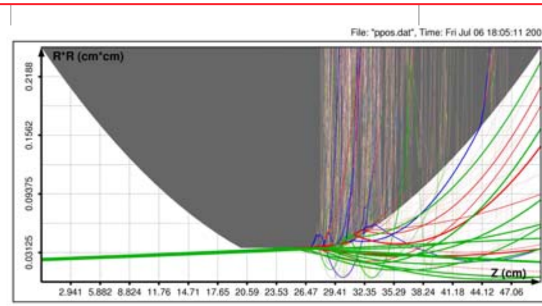


2 : CT2

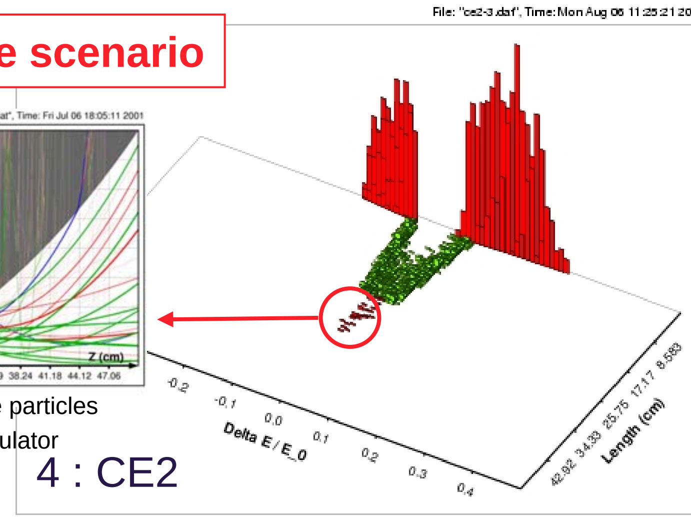
Looking for the worst-case scenario



3: CE1



Up to 1% of the energy of these particles can be deposited in the undulator

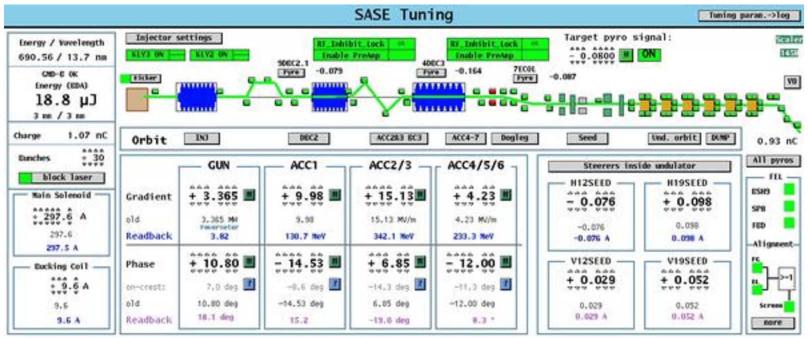


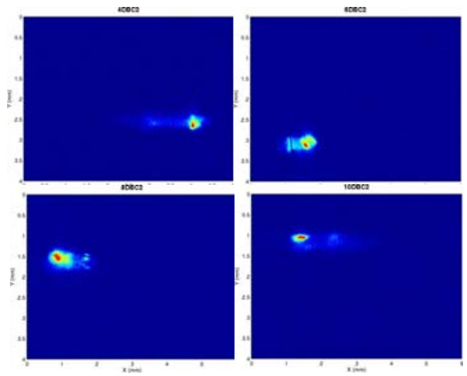
4 : CE2

Distribution of lost primary particles integrated over the azimuthal angle along the collimator surface as a function of the energy deviation

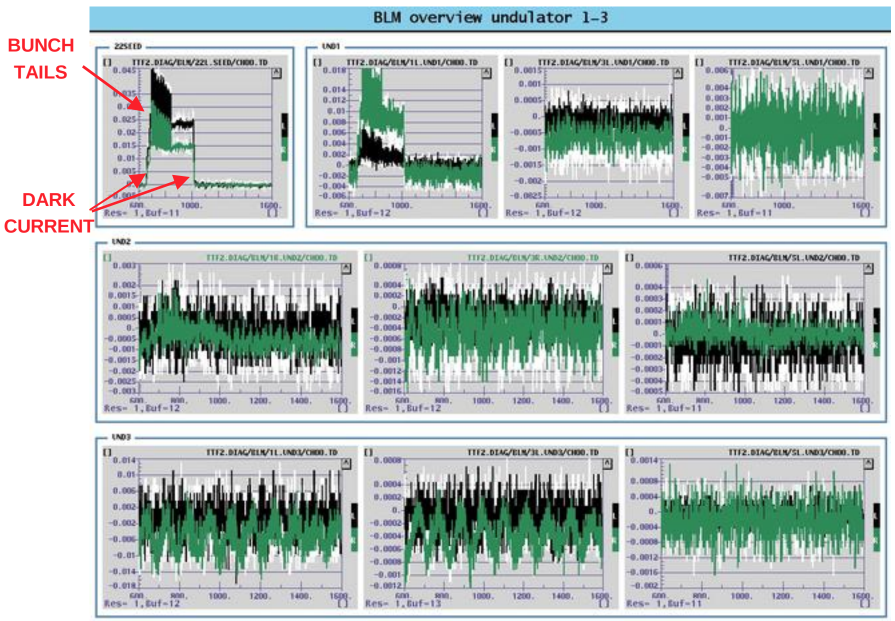
FLASH: Sources of Parasitic Particles

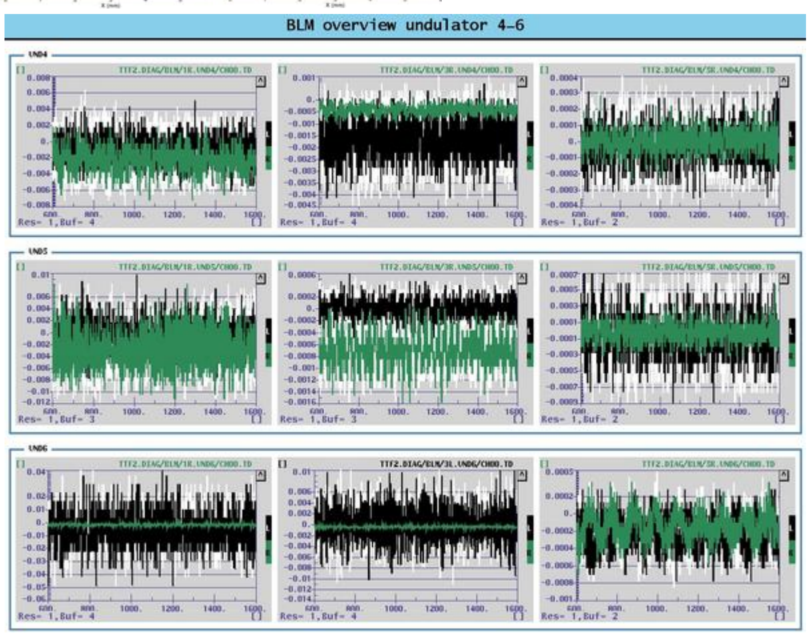
Is it mostly dark current ?





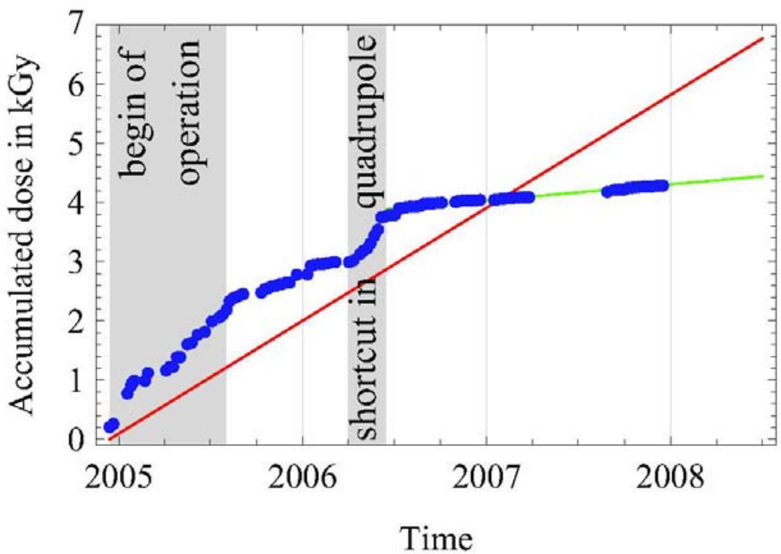
Beam images in DBC2 section.
ACC1 is about -7 degree off-crest





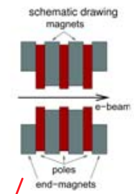
12.04.2009. User operation, 13.7 nm (beam energy about 690 MeV), 30 bunches (bunch charge about 1 nC).

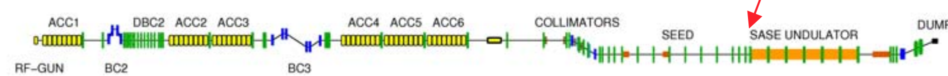
FLASH: Undulator Demagnetization



Averaged accumulated dose of the SASE undulator (blue dots) and linear extrapolations based on all data (red curve) and on data since mid of 2006 (green curve).

- 32 thermoluminescense dosimeters (TLDs)
- 5 at every SASE undulator
- 2 at the dosimetric undulator
- weekly dose measurements



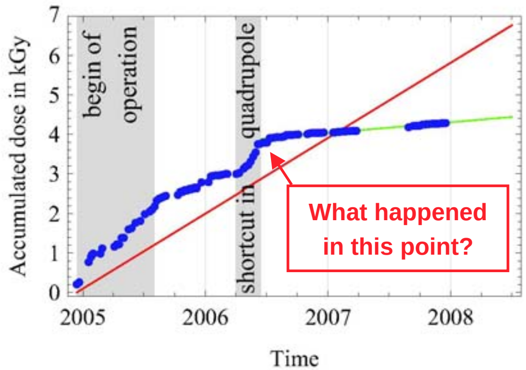


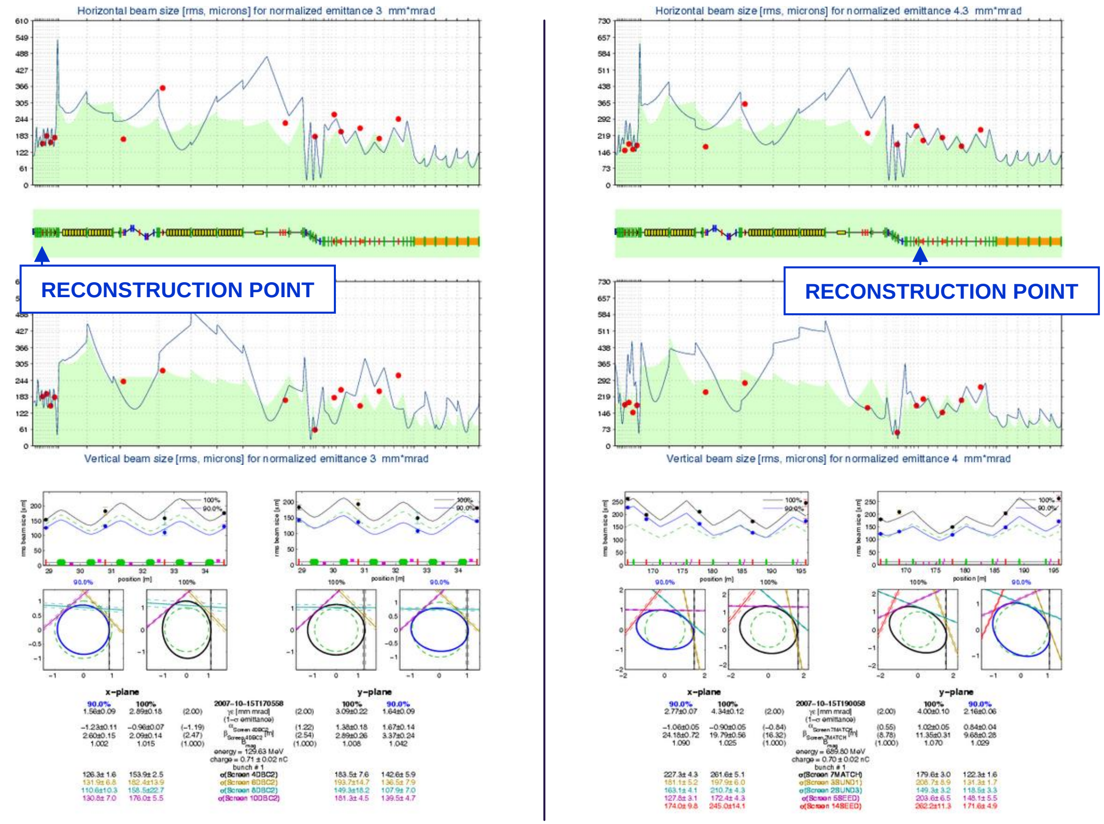
The magnetic field of the dosimetric undulator was measured before its first installation in 2004.
In addition, it was dismounted and remeasured in 2006 and 2007.

By extrapolating the doses accumulated since mid of 2006 the lifetime until a 10% loss of power is reached was estimated to 10 and 30 years for radiation wavelengths of 8 and 30 nm, respectively.

J.Skupin, Y.Li, J.Pflüger, B.Faatz, T.Vielitz, Proceedings of EPAC08, Genoa, Italy, p.2308-2310

FLASH: Beam Optics





During the winter 2005-2006 essential step ahead was made in the understanding of the practical beam dynamics at the FLASH facility (V.Balandin and N.Golubeva):

Almost all magnets were remeasured and their fringing fields were correctly taken into account.

MatLab toolbox for online manipulations with beam optics was written, tested and brought into operations.

New transverse optics with low sensitivity to changes in beam energy and quadrupole settings was developed. This optics was brought into operation in spring 2006 and has shown a superior performance with respect to the previous setup of transverse focusing (not only with respect to lowering losses in the undulator, but also with respect to user operations).

15 October 2007: measured beam sizes along the linac (OTR screens, red dots) compared with theoretical prediction (green areas) and with beam sizes reconstructed using measurements in DBC2 and SEED sections (forward and backward tracking, blue lines).

V.Balandin, N.Golubeva, “Low sensitivity option for transverse optics of the FLASH linac at DESY”, Proceedings of PAC09, Vancouver, BC, Canada

Thank You !!!